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Tensile Flow Behavior in Inconel 600 Alloy Sheet at Elevated Temperatures

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Abstract

Hot deformation behavior of Inconel 600 Ni-based superalloy was investigated up to the peak stress at elevated temperatures. Hot tensile tests were carried out in the temperature and strain rate ranges from 850 to 1150 °C and 0.001 to 1 s^{-1}, respectively. The softening mechanism of dynamic recrystallization was analyzed using the Kocks–Mecking phenomenological approach and the irreversible thermodynamics model. The critical flow stress related to the onset of DRX increased with increasing strain rate due to a higher dislocation generation resulted from a higher strain rate. The constitutive equation relating flow stress, temperature, and strain rate was obtained based on the peak stresses. The constitutive analysis showed that the hot deformation behavior of the Inconel 600 Ni-based superalloy satisfied the hyperbolic sine constitutive equation.

Keywords: IN 600 alloy; flow behavior; dynamic recrystallization; constitutive analysis; stress exponent; activation energy

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1. Introduction

Inconel 600 is a nickel-chromium alloy with good oxidation and corrosion resistance at high temperatures used in the aerospace and nuclear industries, applications that demand strict control of the microstructure of the hot-worked component. Hot deformation behavior of materials is always associated with various interconnecting metallurgical phenomena, such as work hardening, dynamic recovery (DRV), dynamic recrystallization (DRX). Changes in the microstructure of an alloy could also contribute to its workability [1], which is sensitive to the initial microstructures and deformation conditions, particularly temperature and strain rate.

During hot deformation, flow stress is a function of dislocation density after yielding. In the stress-strain relation, the flow stress increases and reaches a peak value, indicating that a dynamic equilibrium between hardening and softening occurs during hot deformation. To optimize the plastic deformation processes, understanding the characteristics of hot deformation is important for controlling microstructural evolution during hot working. In the present work, the stress–strain curve up to the peak stress is analyzed using the Kocks–Mecking phenomenological approach [2] and the irreversible thermodynamics model [3]. The constitutive behavior is also investigated.

2. Experimental

The Inconel 600 Ni-based superalloy sheet used in this work, with a thickness of 3 mm in annealed condition, was provided by American International Metals (USA). The analyzed chemical compositions were (wt %) Ni–15.9Cr–9.41Fe. The original microstructure of the sheet is given in Fig. 1. Sheet type tensile specimens were machined to a gauge length and width of 20 and 3 mm, respectively. Hot tensile tests were conducted on a Gleeble-3500 thermal simulation machine at temperatures ranging from 850 to 1150 °C, at constant strain rates varying between 0.001 and 1 s^{-1}. Specimens were heated to the test temperature and kept for 3 min before hot tension.

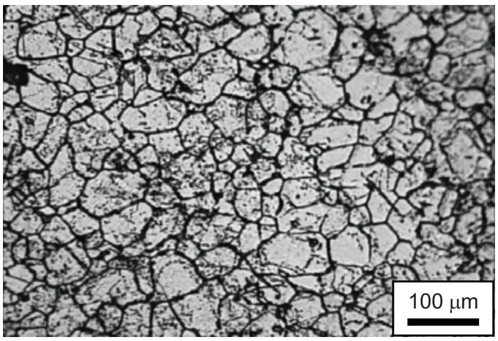

Fig. 1. Optical image of the initial microstructure of the Inconel 600 alloy.

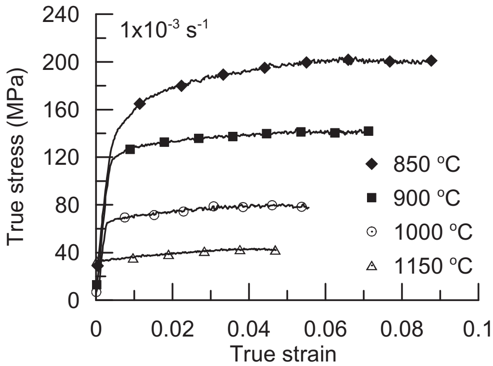

Fig. 2. Stress–strain curves at a strain rate of 0.001 s^{-1} and various temperatures.

3. Results and Discussion

3.1. Flow Behavior

Fig. 2 illustrates the stress–strain curves up to the peak stresses obtained at a strain rate of 0.001 s^{-1} and various temperatures. The effect of the strain rate on the true stress–strain relationship at 900 °C is shown in Fig. 3. The flow curves exhibit the typical flow behavior with dynamic softening. The flow stress increases and reaches a peak value. The slope of stress–strain curve determined at constant strain rate and temperature corresponds to the work hardening rate. At higher strain rates (or lower temperature), hardening is more obvious, whereas at lower strain rates (or higher temperatures), a dynamic equilibrium between hardening and softening takes place at the early stage of deformation. Fig. 4 shows the variation in the peak stress as a function of temperature at various strain rates. The stresses increase with increasing strain rate at a fixed temperature. Moreover, they increase with decreasing temperature at a given strain rate. However, the extent of decrease depends on the temperature. The effect of the strain rate on the stresses is more pronounced at high temperatures. The peak stress significantly decreases with increasing temperature at high strain rates. In contrast, the differences in the peak stress between different temperatures are much smaller at low strain rates.

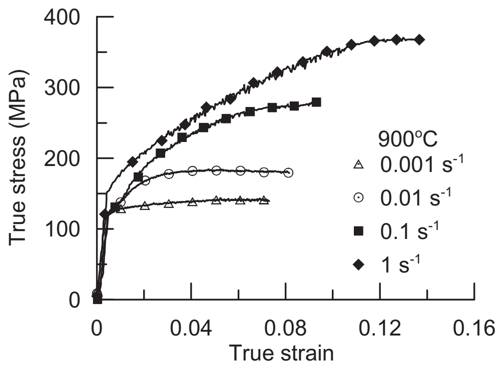

Fig. 3. Stress–strain curves at a temperature of 900 °C and various strain rates.

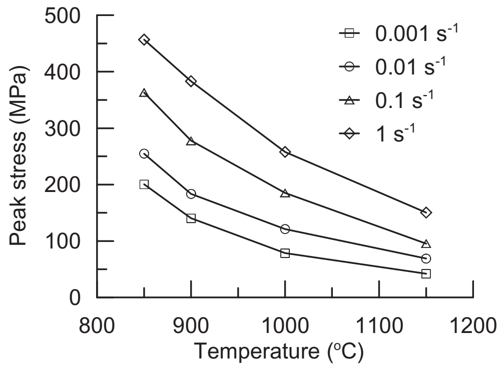

Fig. 4. Peak stress as a function of temperature at various strain rates.

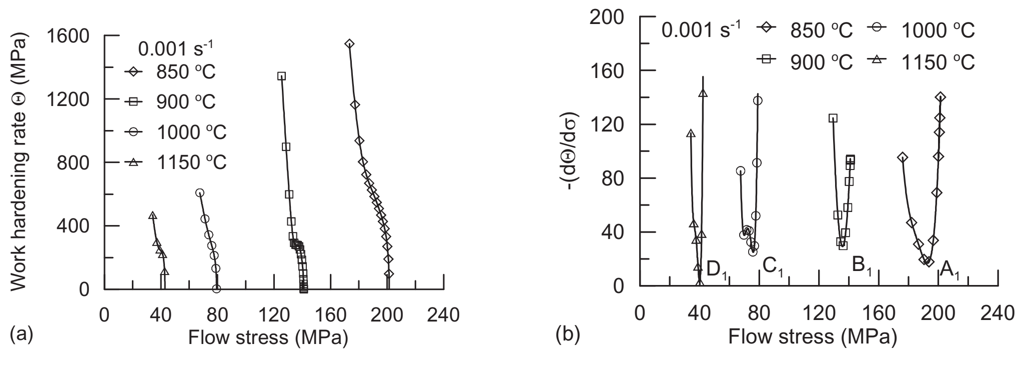

Fig. 5. (a) Work hardening rate (Θ) as a function of flow stress (σ); (b) the flow stress dependence of $-(d\Theta/d\sigma)$ for the Inconel 600 alloy tested at 0.001 s^{-1} and various temperatures.

3.2. Dynamic recrystallization

Based on irreversible thermodynamics, Poliak and Jonas [3] proposed a model to associate the onset of DRX with deformation. In this model, a maximum local stored energy and a minimum dissipation rate value must be satisfied for the onset of DRX. The corresponding location on the flow curve is defined by the point of inflection on the Θ–σ plot ($\Theta \equiv d\sigma/d\varepsilon$, where ε is the strain). The associated point corresponds to the minimum value on the curve of $-(d\Theta/d\sigma)$ versus σ. The corresponding plots are given in Fig. 5 for the specimens tested at 0.001 s^{-1} and various temperatures. The critical points of A_1–D_1 marked in Fig. 5b indicate the onset of DRX. The critical flow stress related to the onset of DRX increases with decreasing temperature. Since the DRX phenomenon is sensitive to energy accumulation, deformation at low temperatures causes less energy accumulation for the nucleation and growth of the dynamically recrystallized grains. The stress concentration is difficult to be relaxed at low temperatures due to the increased severity of dislocation pile-ups. These pile-ups lead to more serious strain hardening and a higher flow stress. Therefore, higher stresses were required to initiate DRX for deformation at lower temperatures.

The Θ–σ and $-(d\Theta/d\sigma)$–σ plots given in Fig. 6 illustrate the effect of the strain rate on the onset of DRX at 900 °C. The critical points of A_2–D_2 (Fig. 6b) mark the onset of DRX. These points reveal that the critical flow stress characterizing the onset of DRX increases with increasing strain rate. This trend attributed to the fact that the dislocation generation rate increases with increasing strain rate, leading to a more significant hardening effect and a higher flow stress.

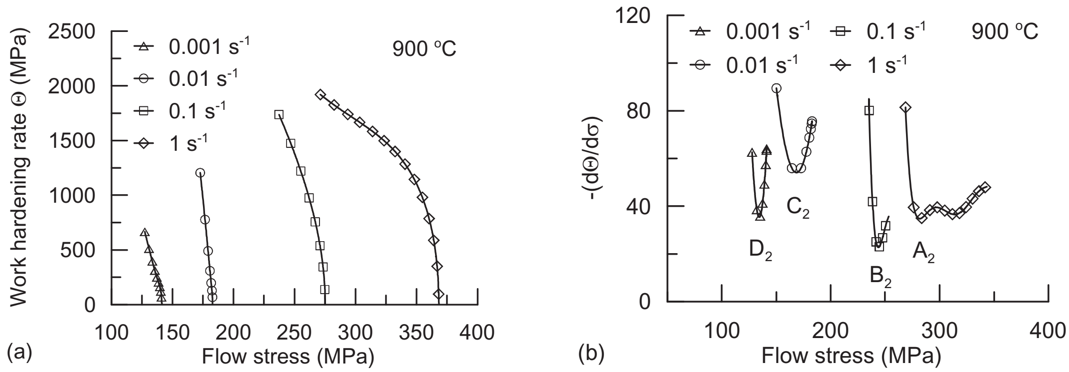

Fig. 6. (a) Work hardening rate (Θ) as a function of flow stress (σ); (b) the flow stress dependence of $-(d\Theta/d\sigma)$ for the Inconel 600 alloy tested at 900 °C and various strain rates.

3.3. Constitutive analysis

The Arrhenius equation is widely used to describe the relationship between the strain rate, flow stress, and temperature at elevated temperatures. The relation between the flow stress, deformation temperature, and strain rate is generally expressed by the hyperbolic sine law [4, 5]

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^n \exp\left[\frac{-Q}{RT}\right] \tag{1}$$

where A (s^{-1}) and α (MPa^{-1}) are constants, σ is the flow stress (MPa), n is the stress exponent, and Q is the activation energy. The rate-controlling mechanism may be evaluated on the basis of the activation energy. Taking the natural logarithms of both sides of Eq. (1) yields:

$$\ln[\sinh(\alpha\sigma)] = \frac{1}{n}\ln\dot{\varepsilon} + \frac{Q}{nR}\left(\frac{1}{T}\right) - \frac{1}{n}\ln A \qquad (2)$$

The value of α may be chosen in such a way that parallel lines would be obtained from the curves of $\ln\dot{\varepsilon}$ versus $\ln[\sinh(\alpha\sigma)]$. n is the slope of the plot of $\ln\dot{\varepsilon}$ versus $\ln[\sinh(\alpha\sigma)]$ at constant strain and temperature. The value of Q can be calculated using the slope of the plot of $\ln[\sinh(\alpha\sigma)]$ versus $1/T$ at constant strain and strain rate.

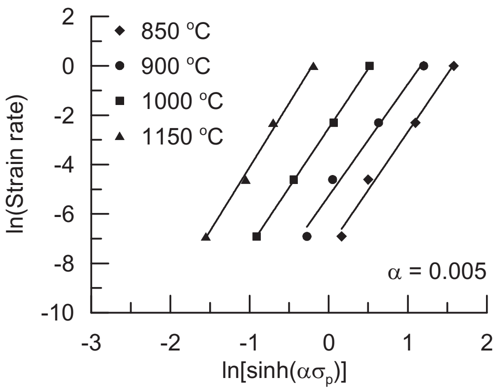

Fig. 7. Variation in $\ln\dot{\varepsilon}$ as a function of $\ln[\sinh(\alpha\sigma_p)]$ at various temperatures.

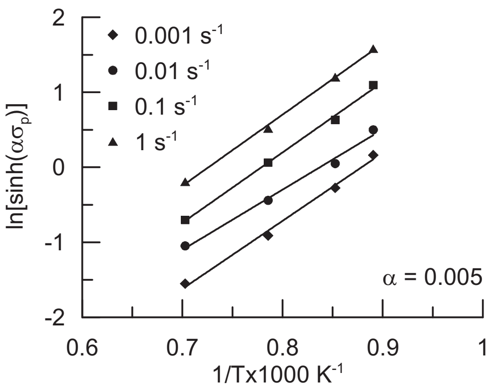

Fig. 8. Variation in $\ln[\sinh(\alpha\sigma_p)]$ as a function of reciprocal temperature.

Fig. 7 shows the relationships between the logarithmic peak stress ($\ln[\sinh(\alpha\sigma_p)]$) and the logarithmic strain rate ($\ln\dot{\varepsilon}$). The value of α, that makes the best fit of the experimental data, is obtained as 0.005 MPa^{-1}. The average value of the stress exponent n is 4.8, with a maximum deviation of approximately 5.7%. Climb-controlled dislocation creep could be a dominant deformation process for the Inconel 600 alloy sheet [6]. Changes in the peak stress as a function of reciprocal temperature is given in Fig. 8. The calculated activation energy Q using the slopes of the plots in Figs. 7 and 8 is approximately 385 kJ/mol.

The constitutive equation can be related to the Zener–Hollomon parameter Z, which is defined as:

$$Z = \dot{\varepsilon}\exp\left[\frac{Q}{RT}\right] = A[\sinh(\alpha\sigma)]^n \qquad (3)$$

Taking the natural logarithms of both sides of Eq. (2) yields:

$$\ln Z = \ln A + n\ln[\sinh(\alpha\sigma)] \qquad (4)$$

Eq. (4) indicates that a linear relation between $\ln[\sinh(\alpha\sigma)]$ and lnZ should exist. The linear relationship between $\ln Z$ and $\ln[\sinh(\alpha\sigma_p)]$ shown in Fig. 9 indicates that the relation of peak stress with the strain rate and temperature well satisfies Eq. (4). The coefficient of determination R^2 of the fit is 0.99. By substituting the calculated parameters into Eq. (1), the constitutive equation of Inconel 600 alloy sheet can be expressed as:

$$\dot{\varepsilon} = 4.5\times10^{14}[\sinh(0.005\sigma_{\mathrm{p}})]^{5.0}\exp\left[\frac{-385000}{RT}\right] \tag{5}$$

The flow stresses calculated using Eq. (5) were compared with the measured flow stresses, as shown in Fig. 10. It is clear that the calculated stresses match the measured stresses well. The dashed line indicates a perfect match between the calculation and measurement. The constitutive equation obtained in this work gives reasonable fit to the measured values.

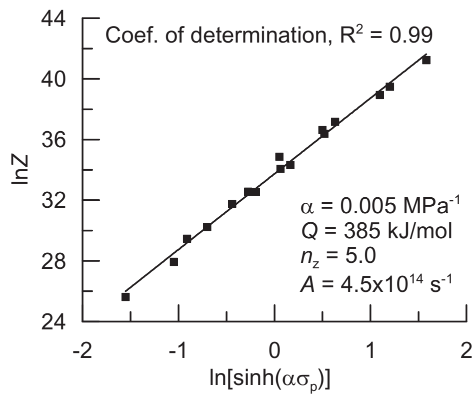

Fig. 9. The variation in Z parameter as a function of ln[sinh($\alpha\sigma_p$)] in Inconel 600 alloy sheet.

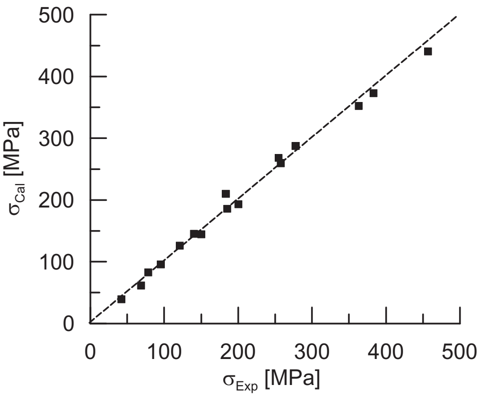

Fig. 10. Comparison between measured and calculated peak stresses.

4. Conclusions

The peak stresses of Inconel 600 alloy sheet in hot tension depended on the strain rate and temperature. The stresses increased with increasing strain rate and decreasing temperature. The critical flow stress related to the onset of DRX decreased with increasing temperature and decreasing strain rate. The hot deformation behavior of the Inconel 600 alloy sheet satisfied the hyperbolic sine constitutive equation.

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